

The FEW-Nexus city index – Measuring urban resilience



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HIGHLIGHTS

- Development of indices to identify and compare urban FEW nexus.
- Monitoring, planning and managing the urbanization process in FEW nexus sectors.
- Operationalization and integration of equity in the FEW nexus analysis.
- Decision support for urban institutions for the development of political measures.

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ABSTRACT

Current global developments put increasing ecological, economic and social pressures on urban systems. The density of urban areas concentrates these pressures especially on food, energy and water (i.e., the FEW nexus) resources as if in a ‘burning glass’. The ability to confront these challenges significantly depends on the resilience of an urban area, which is to a large degree managed by institutions with the objective of protecting social cohesion and minimizing ecological pressure. Urbanization and climate change, however, strain social cohesion by exacerbating social vulnerabilities and disproportionately affecting those already marginalized. Justice and equity are thus essential preconditions for the development of resilient urban concepts and must be considered in a comprehensive nexus management approach. For this purpose, two indices are developed based on the UN-Habitat City Prosperity Index, with a specific focus on integrating the nexus-relevant indices (i.e., the infrastructure development index and the environmental sustainability index) with a weighted equity index. The World and Region Prosperity City Index (WCPI, RCPI⁵) and the Nexus City Index (NXI) enable decision makers to more readily compare global and local city resiliences without reducing the underlying complexity of the analyzed FEW system.

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1. Introduction

The growing world population and rising income levels perpetuate a global trend towards more resource-intensive consumption patterns, which will significantly strain the regenerative capacity of renewable resources [1–5]. The density of urban areas concentrates these pressures as if in a ‘burning glass’ [6–9], turning urban centers into “hotbeds of GHG emissions and vulnerability [10].” Over half of the world population currently lives in urban environments, and it is expected that the trend towards urbanization will continue in the future, especially in less developed countries [6,11,12]. Between 1950 and 2000, the urbanization level in developed countries increased from 17.6% to 40.1%, and it is expected to reach over 50% by 2020 and over 64% by 2050 [13]. This increasing

urbanization leads to a spatial centralization of all aspects of human life so that the world “cities today occupy approximately only 0.5% of the total land [14] “but produce 70% of the world GDP, more than 60% of global energy consumption, 70% of world GHG emissions, and 70% of global waste [14]. The focusing of human life also forces more than 827 million people to live in slums that often lack adequate water and sanitation services [15]. This number will likely increase to over 880 million in 2020 [15,16].

Cities are thus of central importance for sustainable development and they are increasingly at the center of the food-energy-water nexus (FEW nexus) discussion [17–23]. The direct interdependencies among those resources [22,23], especially in urban areas, require an integrated approach for their management based on shared and jointly interpreted data [4,24,25]. Given its objective as defined during the Bonn 2011 Nexus Conference to achieve “improved water, energy and food security” through “integrated

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management and governance across sectors and scales [26]”, the FEW nexus approach is generally considered as a supporting instrument to a green economy [26] and thus towards resilient global development. Cities are the spearhead of this transformation process. Urban lifestyles offer attractive options, but the highly aggregated nature of a city often leads to higher resource intensity, and the concentration of consumption and waste production poses additional challenges for sustainable city design [6,7,21,27,28]. Yet, despite all these challenges, urbanization also provides “unprecedented opportunities to enhance the resilience and ecological functioning of urban systems [29].”

A major challenge in managing the FEW nexus within cities is that cities have no clearly defined boundaries separating the city system from the surrounding system [6,28]. Cities are connected to their environment by a complex infrastructure created to solve their resource allocation problem [8,16]. Resource requirements are differentiated as

- (a) *direct* resource requirements (i.e., resources employed and/or discarded within the urban area) and
- (b) *indirect* resource requirements (i.e., resource flows or impacts caused by urban requirements with effects that occur elsewhere) [30]:

“In a totally urbanized world, concentrated in cities, the countryside becomes in effect only a supplier to the cities, that is, to the needs of their human population, rather than being also a place of human settlements. It provides the cities with resources, but also, in the negative sense, it becomes a repository of their waste [31].”

Translated into the management of the FEW nexus, this implies the consideration of (a) an in-boundary FEW resource system and (b) a transboundary system which provides the resources for the city system [7,18]. Especially in highly industrialized economies, this resource infrastructure is embedded in a mass network of further critical infrastructures (e.g., information and communication infrastructures), so that cities essentially comprise the key infrastructure services and productive assets for economic development and growth [32,33]. Because, however, infrastructure services are provided by organizations such as businesses, governments, or nongovernmental institutions [31,34,35], their pursuit of economic efficiency also makes them increasingly vulnerable to technogenic (e.g., power blackouts), natural (e.g., hurricanes, floods, etc.), or intentional (e.g., terrorism) disruptions [33]. Hence, the resilience of the infrastructure [33] constitutes an important precondition not only for the sustainable management of the nexus resources in cities, but also for socially equitable access to FEW resources [36] and thus social cohesion in a wider sense [37].

This view is also supported by the New Urban Agenda¹ of the Habitat III (United Nations Conference on Housing and Sustainable Urban Development²) in 2016. The UN stated that cities and human settlements have to “fulfill their social function, including the social and ecological function of land, with a view to progressively achieve the full realization of the right to adequate housing, as a component of the right to an adequate standard of living, without discrimination, universal access to safe and affordable drinking water and sanitation, as well as equal access for all to public goods and quality services in areas such as food security and nutrition, health, education, infrastructure, mobility and transportation, energy, air quality, and livelihoods [16].”

Furthermore, especially in less developed countries, scarce resources are often disparately allocated to high productivity activ-

ities with insufficient consideration of the larger population [13,38]. The discussed inequalities can create a lack of social cohesion as the UN stated in the New Urban Agenda. Less cohesion among citizens [16], however, may reduce the benefits of an urban lifestyle and thus increase the overall social costs of the centralization which is often considered the essence of cities [7,39]. Resolving this challenge will require a mutual understanding of justice as an important component in achieving sustainable development.

As alluded to above, the ‘heart’ of the city, i.e., its critical infrastructures, is designed and operated by institutions [40], which therefore significantly determine the quality of life in complex city environments [35]. In the Nexus City Index (NXI) developed by us, we therefore not only consider the FEW resources, but furthermore also weight the index in the measuring model with an equity index. For this purpose, the indices are based on the UN-Habitat City Prosperity Index, but specifically integrate the nexus-relevant indices (i.e., the infrastructure development index and the environmental sustainability index) with a weighted equity index. The World and Region Prosperity City Index (WCPI, RCPI⁵) and the Nexus City Index (NXI) enable decision makers to more readily compare global and local city resiliences without reducing the underlying complexity of the FEW system analyzed.

2. The meaning of cities – Challenges of the urban age

UN-Habitat and the German Advisory Council on Global Change (WBGU), among others, see the world moving towards an urban age [40,41], especially in developing countries [42], where most of the industrial growth occurs in urban centers. Urban areas will become the central organization form for nearly all human societies [41]. Their dynamic and intense vitality transforms these areas into centers of prosperity [40]. Urban prosperity, in the view of the UN, is not only an economic category but “a socially broad based balanced and *resilient* ... development [40]” that requires urban institutions to tighten the links between individuals and society [40]. However, cities are not only possible centers of urban prosperity but also zones “for those who lack power [and] those who are disadvantaged” [43]. In the 30 least developed countries, 80% of the urban population live in slums [44]. In urban areas, the inequality challenges of the globalized world [45] are concentrated. Hence, governance structures are needed that direct urban development, especially with respect to the management of the FEW resources towards resilient urban systems as demanded by the UN Habitat III new urban agenda [16].

2.1. Urban resilience

The resilience (from the Latin *resilire* = to rebound) of an urban system is defined as “the ability of a system to absorb disturbance and still retain its basic function and structure [46].” Humans are resilient if their psychological strength enables them to handle extreme events and stress, whereas a forest is considered resilient if it can recover from a fire storm [47]. A differentiation can thus generally be made between ecological and sociological resilience [48]. *Ecological resilience* is further broken down into (a) ecological resilience (i.e. resilience as a measure of the “magnitude of disturbance that can be absorbed before the system redefines its structure by changing the variables and processes that control behavior [48]”, i.e., a system is flipped into another regime of behavior [48]), and (b) engineering resilience (i.e. resilience as the ability to return to a steady state after external shocks [48]). *Sociological resilience*, in contrast, refers to the ability of societies to absorb external shocks, without changing substantial and essential system functions [46,49]. The resilience of a social system can be defined as “the capacity of a system to absorb disturbance and

¹ <https://habitat3.org/the-new-urban-agenda>.

² Quito, Ecuador, from 17 to 20 October 2016.

reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks [50].” In urban areas, resilience is thus to a significant degree determined by inclusive economic and political institutions [16] and by goal 1 and 11 of UN-SDGs (United Nations Sustainable Development Goals (UN-SDGs) [51]), which enables social cohesion to tighten the links between individuals and society, and which prevents exclusion or marginalization of the least advantaged [16,40] by strengthening “the resilience of communities [51].”

Social equity is thus essential for a resilient urban concept [16]. Comprehensive socio-economic-ecological resilience of FEW nexus urban systems requires both ecological resilience of the surrounding FEW system as well as social resilience of the urban system to manage the challenges of a globalized economy.

A resilient system is characterized by the fact that it influences and is influenced by inclusive political and economic institutions, which manage and organize the urban system, minimize ecological pressure and protect social cohesion after ecological and/or socio-economic shocks (Fig. 1).

Social and natural shocks can create an exclusive regime in a city if the shocks cannot be mitigated adequately by the urban institutions [40]. A resilient urban social-ecological system has “a greater capacity to continue providing us with the goods and services that support our quality of life while being subjected to a variety of shocks [46].” With the increasing complexity of urban systems, it becomes increasingly necessary to reshape the system towards higher resilience by promoting adequate technologies and institutions to cope with the progressing challenges [16,47,52]. This view is also shared by the UN Habitat III conference: “Cities and human settlements [should be] planned, designed, financed, developed, governed, and managed [to] foster resilience and protect the environment [16].” And they should therefore work on realizing the UN Sustainable Development Goal 11 of “making cities and human settlements inclusive, safe, resilient, and sustainable [16].”

2.2. Monitoring resilience

To provide the necessary information, a resilient management concept should account for changes in any specific place but should also be able to detect feedback responses elsewhere in the socio-economic-ecological system. The proposed urban management concept delivers such data about urban development [53].

In its State of the World's Cities Report, the UN demands a redefinition of urban prosperity: “Re-thinking prosperity in those terms requires a shift away from the current dominant perspective, which is outdated and unsustainable on many grounds with its combination of cheap fossil fuel, heavy dependence on the motor car, highly segmented urban forms, socially and economically segregated spaces, endless urban peripheries that consume land, resources and in many cases natural protected areas – and all largely steered by private, not public interest [40].” To address this challenge, the UN defined five key issues to capture different facets of urban life. These issues are of central importance for a resilient development of urban systems: productivity, infrastructure development, quality of life, equity and social inclusion, and environmental sustainability. For each of these key issues, the UN developed an index to monitor their development (Table 1) [40].

Energy, water and land, the key issues relevant to the nexus concept, are important elements of urban planning models [54–56], because as the World Business Council on Sustainable Development (WBCSD) states: “Water, energy and food are intrinsically interrelated [52].” It is important to note that often food and land are used almost interchangeably as resources within the nexus concept. Food, however, in contrast to water, energy and land, does

not constitute a natural resource, but is, instead, a derivative resource which depends on the sufficient availability and quality of land, energy and water. The aspect of food security is thus captured indirectly in the proposed index approach.

What might appear to be an effective policy in one dimension may be harmful for others or to the whole ecosystem. Reasonable solutions for the socio-economic system may be disastrous for the ecosystem. To achieve urban sustainability, these different aspects and their interlinkages must be comprehensively accounted for. With relevance to the FEW nexus, the UN-Habitat approach specifically considers the following [40]:

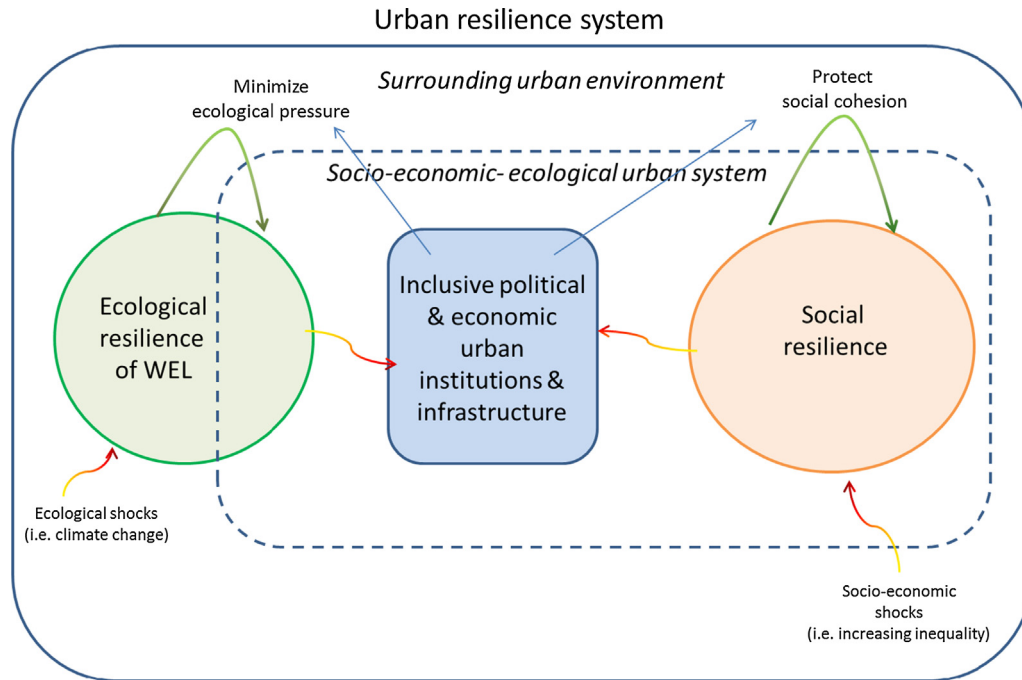
- The *productivity index* measures the contribution of the rise of productivity to economic growth [40].
- The *infrastructure index* [40] measures whether an urban area has an adequate infrastructure for an increase in productivity. This index is important because in “developing countries, virtually all industrial growth is in the big cities [44].” This index also includes the FEW sectors of water and sanitation infrastructure.
- The *quality of life* index measures the development of the social cohesion of urban society [40].
- The *equity index* indicates whether the result of an increase in productivity is distributed equally among the members of urban society. This index is important, because the “stark polarization between rich and poor is one of the most striking features of developing country cities [44].” Therefore the UN stresses that the cities of the developed and developing world must “realize that equity has a significant impact on economic performance, since the greater the degree of equity [57], the greater the chances of a fuller, more efficient use of available resources, including skills and creative talent [40].” UN-Habitat III conference emphasizes the immanent negative feedback of inequality [40], because it negatively affects urban prosperity: “A review of inequality in cities – [urban divide]³ – reveals a steady increase over the long term, as well as in recent decades. Paradoxically, this has occurred as wealth rose enormously around the world [40].” We will therefore account for inequality in our Nexus City Index.
- Additionally, with the *environmental sustainability index*, the UN considers an important aspect of urban prosperity. The UN focuses in particular on energy and land issues and thereby considers FEW aspects in its environmental sustainability index [40].

These five indices form the basis for the proposed Nexus City Index, which reflects the resilience of the urban FEW sector system.

3. The nexus city index

UN-Habitat calculated its five indices for 69 cities, 22 of which are located in Europe, two in North America, five in South America, 18 in Asia, 20 in Africa and two in Oceania. On this data basis, we developed our Nexus City Index (NXI_{city}) to measure the prosperity and sustainability of the FEW nexus of the 69 cities and their regions. Measurability of sustainability constitutes the core objective of our assessment approach and the implementation of a sustainable management concept for the FEW nexus sectors, because “if current systems of economic indicators do not clearly signal that the economy is on an unsustainable path, the policy errors will be made and perpetuated [59].” The NXI_{city} serves to avoid these errors.

³ More information about the urban divide in [58] UN-HABITAT. State of the World's Cities 2010/2011– Cities for All: Bridging the Urban Divide. London: UN Habitat; 2010. p. 244.



Source: Authors, 2016 based on Paul Cline, <https://www.pinterest.com/pin/29906784996905891/>

Fig. 1. Urban resilience system.

Table 1
Defining prosperity.

Defining a prosperous city – UN Habitat		UN-Habitat
Key issues	A prosperous city is one that provides	Indices
Productivity	Productivity contributes to economic growth and development, generates income, provides decent jobs and equal opportunities for all by effective economic policies and reforms	Productivity Index
Infrastructure development	Provides adequate infrastructure – water, sanitation, roads, information and communication technology	Infrastructure Development Index
Quality of life	Enhances the use of public spaces in order to increase community cohesion, civic identity, and guarantees the safety and security of lives and property	Quality of Life Index
Equity and social inclusion	Ensures the equitable distribution and redistribution of the benefits of a prosperous city	Equity Index
Environmental sustainability	Values the protection of the urban environment, uses energy more efficiently, minimizes pressure on surrounding land and natural resources, enhances the quality of the environment	Environmental Sustainability Index
Source: UN Habitat 2012		IEK-STE 2016

We use in our analysis a top down urban FEW nexus approach which aggregates the FEW sectors to a single indicator, and thereby enables the direct comparison of developments within the FEW sectors with developments in other sectors. We apply this top-down approach to the 69 urban areas considered within the 2012 UN Habitat Programme. The FEW nexus approach focuses on urban resilience, which is addressed in Goal 11 of the UN Sustainable Development Goals (SDGs) for ecologically and socially resilient urban systems capable of absorbing disturbances while retaining their basic functions and structures.

Besides the Nexus City Index (NXI_{city}), we also developed the World City Prosperity Index (WCPI), the Regional City Prosperity Index ($RCPI^5$) and a regional city index (NXI_{region}) to analyze the resilience of the various regions of the world and the world city index (NXI_{world}). These two indices enable us to compare the development of the FEW nexus sectors with the overall development of UN-Habitat prosperity indices.

As discussed above, the regional City Prosperity Index ($RCPI^5$) is built on the five dimensions of the UN-Habitat City Prosperity Index (CPI^5): productivity index, quality of life index, infrastructure index, environment index, equity index. These indices are aggregated to an overall Regional City Prosperity Index ($RCPI$) and a

World City Prosperity Index (WCPI) to compare the prosperity of the individual cities with the regional average city and the average world city.

The Nexus City Index is also based on the UN-Habitat World City Prosperity Index, but aggregates the following UN-Habitat indices to a new nexus index, which represents the nexus issues (water, energy and land) complemented with the equity index to account for effects of inequity as a significant threat to social stability [60].

Infrastructure development index (water, sanitation).

- Equity index, weighting factor based on the cities' Gini coefficient.
- Environmental sustainability index (energy, land).

The UN-Habitat City Prosperity Index is defined between 0 and 1. Cities with a CPI above 0.900 display very solid prosperity, whereas cities with very weak prosperity have a CPI below 0.500. The infrastructure development index accounts for the water and sanitation infrastructure as one of the major nexus management aspects. The environmental sustainability index contains the nexus sectors of energy and land. Hence, the two indices contain informa-

tion about the respective development of the analyzed cities relative to the FEW nexus sectors. In addition to water, energy and land, we further considered equity in our nexus index to include the links between individuals and society. The nexus city index thus allows an analysis of the nexus system for the selected cities and institutions.

The *Regional City Prosperity Index (RCPI)* and the *World City Prosperity Index (WCPI)* translate the UN-Habitat-based indices into comparable regional and world indices.

$$RCPI_r^5 = \sqrt[n_r]{\prod_{i=1}^{n_r} CPI_{i,r}^5},$$

r = Europe(22), North(2) & South America(5),
Asia(18), Oceania(2), Africa(20),
 i = cities of the regions
 n = number of analyzed cities in the specific region(r)

$$WCPI^5 = \sqrt[N]{\prod_{i=1}^N CPI_i^5}, N = 69, \text{ total number of analyzed cities}$$

Nexus City Index

$$NXI_{city} = \sqrt[n]{\prod_{i=1}^n x_i^{w_i}},$$

x = habitat subindices(infrastructure, equity, environment)
 w_i = specific weight of the individual city(i)
for the equity index

The exponent of the root is the sum of the city weights.

$$w = \sum_{i=1}^N w_i, i = \text{weights of the individual city}$$

$$w_i = \frac{HDI_{country_i}}{\text{city equity index}_{country_i}}$$

Our equity weights (Table 2) w_i^R in the Nexus City Index are derived from the relation of the human development index (HDI) to the equity index of the UN-Habitat prosperity index. This relation describes in how far the equity level measured by the UN Habitat equity index lags behind the human development level of the respective country. We thus assess the degree to which the human development in a specific country is comparatively better or worse than the respective level of equity as measured by the UN Habitat equity index – i.e., whether wealth as measured by the human development index (HDI) is distributed equally among the city population. Because research has shown that social justice is of special importance for the resilient development of urban systems, we use specific equity weights for the equity index to weight the equity range with a slightly higher weight than the other indicators.

Table 2
Weights of the Nexus City Index.

Weights of the Nexus City Index	
HDI in % of equity index	Derived weighting factors for the Nexus City Index
<0.95	0.5
0.95–1.04	1.0
1.05–1.24	1.2
>1.24	1.5

Source: Own calculation 2016 based on UN Habitat, 2012, UNDP, 2014.

The values of the Nexus City Index are defined between 0 and 1. Furthermore, we grouped the cities into six major clusters depending on their city prosperity index classification, from excellent FEW nexus city prospects to very weak FEW nexus city prospects.

1. Cities with largely resilient nexus prospects (NXI_{city} : above 0.900)

The water and sanitation infrastructure is in very good condition, the equity variations between the citizens are low and the environmental impact of energy production and consumption and land use is relatively sustainable and well managed. The situation of the city can be interpreted as resilient. The city has the ability to assimilate shocks because equity challenges are accounted for.

2. Cities with almost resilient nexus prospects (NXI_{city} : 0.800–0.899)

The city is well on the way to becoming a resilient city. The FEW nexus sectors are in good condition, equity among citizens is sufficient, and land and energy issues display good future prospects.

3. Cities with balanced nexus prospects (NXI_{city} : 0.700–0.799),

The prospects for the city are not yet completely clear. Development in both directions is possible.

4. Cities with vulnerable nexus prospects (NXI_{city} : 0.600–0.699)

The positive prospects are in danger, but the city has institutions which may be able to manage the challenges of the globalized world. The city may still have resilient prospects.

5. Cities with fragile nexus prospects (NXI_{city} : 0.500–0.599)

Prospects are not resilient. The city has limited institutional resources to cope with current global challenges.

6. Cities with very fragile nexus prospects (NXI_{city} : below 0.500)

Prospects are not at all resilient. The city will most likely be unable to compensate the effects of external shocks. The institutional structure of the city does not enable the citizens to react appropriately to globalized interplay.

Based on the nexus indices, we further developed a regional overall index and a world index to compare regional urban developments with average world urban development. In a second step, we calculated the regional overall index based on the NXI_{city} to compare the development of the cities in the various regions of the world:

$$NXI_{region} = \sqrt[n_r]{\prod_{i=1}^{n_r} NXI_{city,i,r,w}},$$

n_r = number of all cities in the various regions :
Europe, North & South America, Oceania, Asia, Africa
 i = cities in the regions(r)
 NXC = Nexus city index of the cities in a region
 w = city weight

In a final step we calculated a World Nexus City Index:

$$NXI_{world} = \sqrt[n]{\prod_{i=1}^n NXI_{city,i,w}}, n = \text{all cities}, w = \text{city weight}$$

4. Results

4.1. The cities

To identify the heterogeneity of regions and the cities within them, for each region we calculated the statistical range of the Nexus City index.

The range (w) is defined as [61]:

$$w = \max_i x_i - \min_i x_i \quad (8)$$

We use this range as a first statistical measure to analyze the distribution of the cities.

4.1.1. European cities

The data sample of the European cities contains 22 cities, of which 17 cities belong to the European Union, three to the former Soviet Union, and one city each from Switzerland and Norway (see Figs. 2–5).

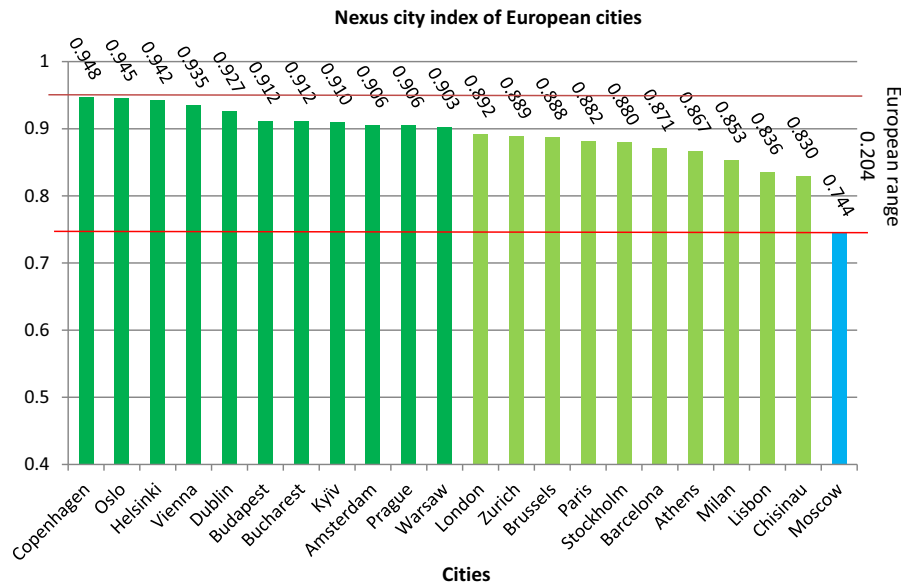
Copenhagen and Oslo are the European cities with the highest NXI of 0.948 and 0.945 of all analyzed cities, whereas the cities of the former Soviet Union (Moscow and Chisinau) have the lowest NXIs in Europe. The Moscow NXI is significantly lower than those of the other European countries. This is mainly due to the fact that the equity index is extremely low. Moscow can thus be considered the least resilient city in Europe. The range of the European values is 0.204. Considering only EU countries reduces the range to 0.112.

The institutional framework of the European Union leads to a more coherent development of the European cities.

4.1.2. North and South American cities

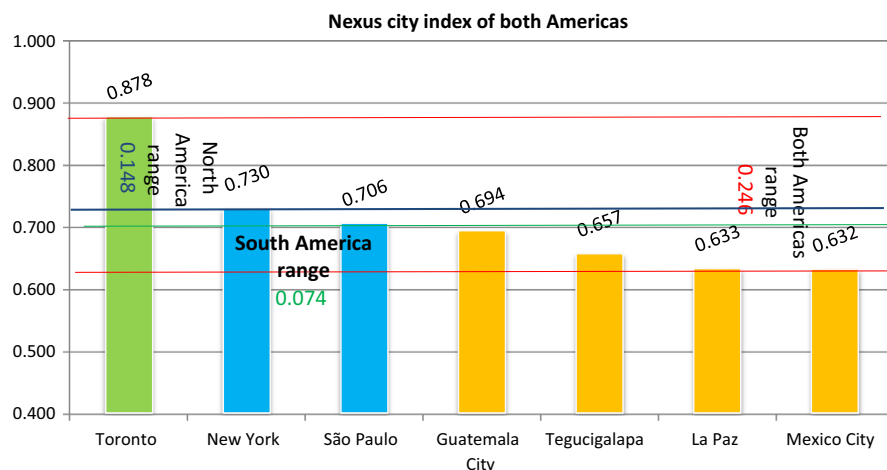
We further analyzed the American cities. In this context, we differentiated between the North American cities of Toronto and New York and the South American cities. However, we summarized the Central and South American cities in one data sample, because the UN data sample contains only one South American city: São Paulo. The Caribbean cities are not represented in the American data sample. We encourage the UN to extend the American data sample by including cities from South America and the Caribbean to provide a broader picture of the urban situation in both Americas.

The current, limited data sample shows that the range of the South American cities (0.074) is smaller than that of the North American cities (0.148). If we analyze the range of both Americas, then the range increases to 0.246, which is higher than the range of the European countries.



Source: UN Habitat, 2012, and own calculations 2016, IEK-STE 2016

Fig. 2. Nexus city index of European cities.



Source: UN Habitat, 2012, and own calculations 2016, IEK-STE 2016

Fig. 3. Nexus city index of both Americas.

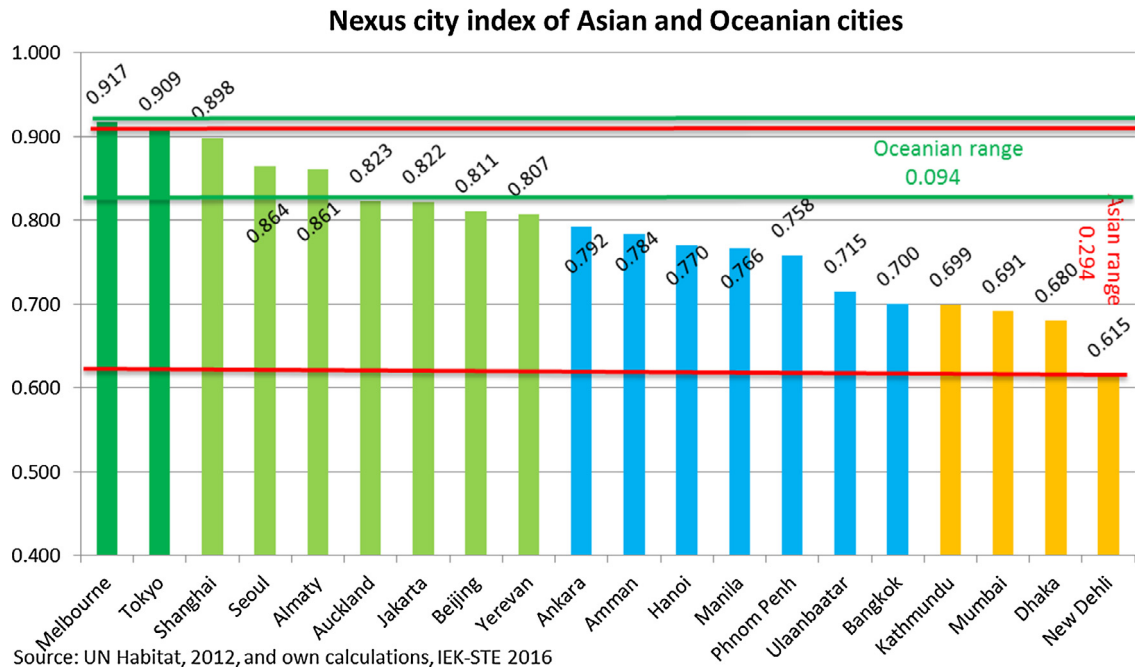


Fig. 4. Nexus city index of Asian and Oceanian cities.

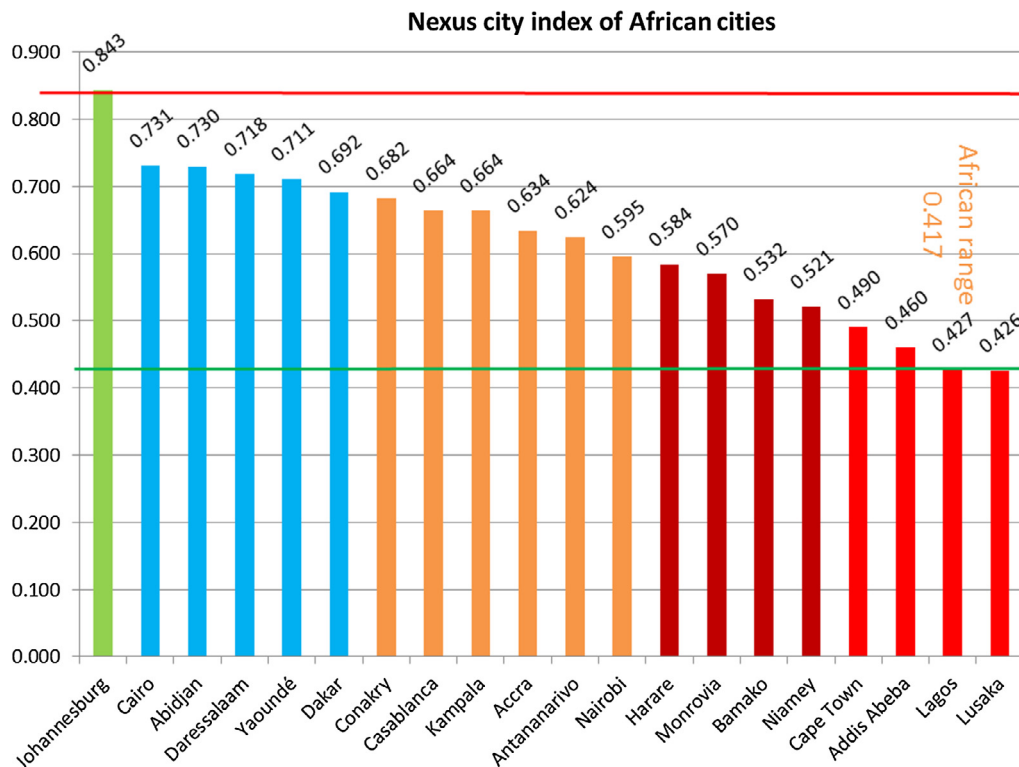


Fig. 5. Nexus city index of African cities.

4.1.3. Asian and Oceanian cities

The Oceanian region is currently represented by two cities: Melbourne and Auckland. The data sample of Asian cities contains 18 cities.

The NXI range of the two (and thus very limited) Oceanian cities (0.094) is small in comparison to the Asian urban areas with a

range of nearly 0.3. The Oceanian cities can be classified as resilient, whereas the picture of Asia is more heterogeneous than that of European and American cities. Tokyo can be considered as a resilient city whereas the data for New Delhi and Dhaka indicate that they will face severe difficulties in dealing with their FEW nexus challenges. The Asian data show that resilience is a function of

the degree of development. The cities (Tokyo, Seoul) in highly developed countries (Japan, Republic of Korea) are more resilient than the cities (Kathmandu, Dhaka) in less developed countries (Nepal, Bangladesh).

4.1.4. African cities

The African data sample contains 20 cities. Not unexpectedly, the African cities have the highest range of all analyzed regions: 0.417.

This wide range reflects the very heterogeneous urban situation in Africa. The scale ranges from the resilient city of Johannesburg to Lagos or Lusaka, which have far from resilient prospects. They have the lowest NXI value of all 69 analyzed cities. South Africa is also the country with the highest internal range of all countries: 0.353 between Johannesburg and Cape Town.

In order to generate a more comprehensive picture, we further analyzed the world regions to allow comparisons with regional FEW nexus resiliences.

4.1.5. Summary – The resilience of the cities of the world

The following Fig. 6 shows the resilience status of the analyzed urban areas.

- **Category 1:** Fig. 6 shows that 13 cities fall into the first group of cities ($NXI_{city} > 0.9$), which are classified as ‘resilient development’. Given their solid level of social inclusion, these cities can absorb socio-economic and ecological shocks in the FEW nexus. This category includes cities from Europe, Oceania and Asia.
- **Category 2:** This category (NXI_{city} : 0.800–0.899) is the largest category and comprises 19 cities, which can be classified as ‘almost resilient’ cities. It is regionally the most heterogeneous group, containing cities from all analyzed regions. The FEW nexus sectors are in good condition and their equity levels suggest they are in a good position to face the challenges of a globalized world.

- **Category 3:** The 13 cities in this category (NXI_{city} : 0.700–0.799) are characterized by ‘balanced’ nexus prospects. Their future development is not yet clear. Development in both directions is possible.
- **Category 4:** This fourth category (NXI_{city} : 0.600–0.699) also contains 14 cities. The cities in this category currently do not have positive, resilient prospects. Strong institutional efforts will be required to prepare these cities for the challenges of a globalized world.
- **Category 5:** The fifth group (NXI_{city} : 0.500–0.599) comprises the cities with fragile nexus prospects, which are not resilient. The five African cities have limited institutional resources to cope with global challenges.
- **Category 6:** This sixth category has very fragile nexus prospects (NXI_{city} : below 0.500). A resilient urban management concept to meet the global challenges and possible ecological and socio-economic shocks is hardly possible for the four cities in this category.

4.2. World regions

We then use the World Region Prosperity City Index (WCPI) and Regional Nexus City Index (NXI_{region}) to compare the development of the regional and world FEW nexus sectors with the overall prosperity development of UN-Habitat indices. Our indices enable us to define the nexus gap and the prosperity gap of the average city of the six world regions by comparing the regional Nexus City Index (NXI_{region}) with the RCPI and the NXI_{World} with the WCPI. The gap between the FEW nexus and prosperity can be described from two perspectives – the FEW nexus resilience perspective and the prosperity perspective. The FEW nexus gap describes the situation when the development of the FEW nexus lags behind the development of productivity and quality of life, whereas the prosperity gap describes the situation, when the development of productivity and quality of life lags behind the development of the FEW nexus. The two gaps thus describe the relative position of the FEW nexus and

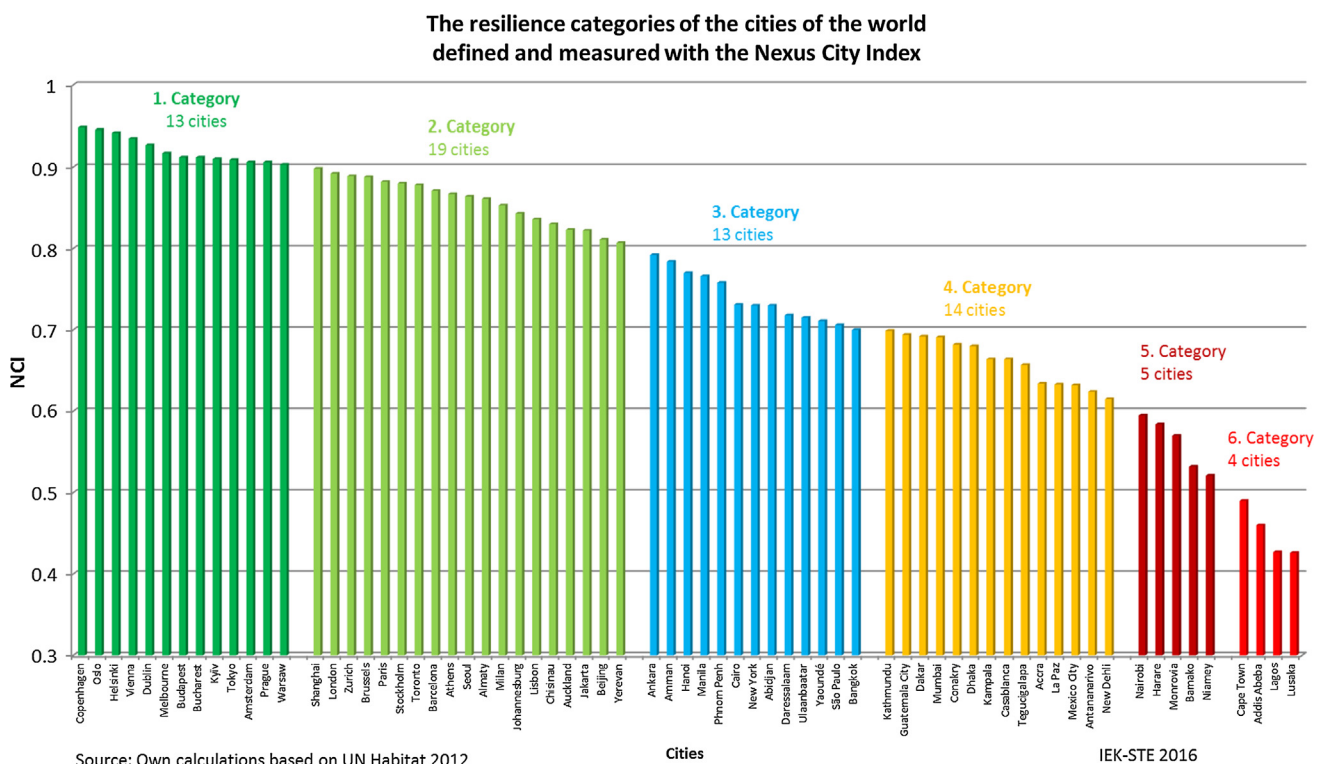


Fig. 6. The resilience categories.

prosperity to each other and thus, in combination, allow the assessment of urban development from a purely FEW nexus centered perspective and from the prosperity nexus perspective.

The nexus gap describes the FEW nexus sectors (ΔN) that do not develop at the same rate as productivity and quality of life (ΔP), whereas the prosperity gap reflects the productivity and quality of life of cities (ΔP) that lag behind the FEW nexus sectors (ΔN). The FEW nexus gap and the prosperity gap can be summarized by the following equations:

$$\begin{aligned} \text{FEW nexus gap} &= \Delta N < \Delta P \\ \text{Prosperity gap} &= \Delta N > \Delta P \end{aligned} \quad (9)$$

The results enable us to identify, whether development of the cities in the various regions is characterized by a FEW nexus gap (NG) (i.e., development in the FEW nexus sectors lags behind the development of productivity and quality of life), or a prosperity gap (PG) (i.e., development of productivity and quality of life lag behind the development in the nexus sectors). The results show that in most regions the NXI is higher than the RCPI⁵ (i.e., a prosperity gap). This also holds true for the world average city. Only in North America and Oceania the RCPI is higher than the NXI_{region} (i.e., a nexus gap). The gap between the two indices is largest in Oceania.

Fig. 7 further shows that, on average,

- cities in Europe, North America and Oceania are above the world average for both indices (RCPI⁵, NXI_{region}),

- whereas, South American and African cities are, on average, below the world average level of both indices.
- Asian cities are for both the NXI_{region} and for the RCPI⁵ above the world average.

5. Statistical summary

This section serves to summarize the findings using the following key statistical figures to express the resilience of the regional urban areas.

To statistically express urban resilience, we calculated the following statistical measures for the four major regions. We summarize North and South America in the data sample as 'Both Americas', and Asia and Oceania to 'Asia + Oceania', because North America and Oceania both only contain two data points.

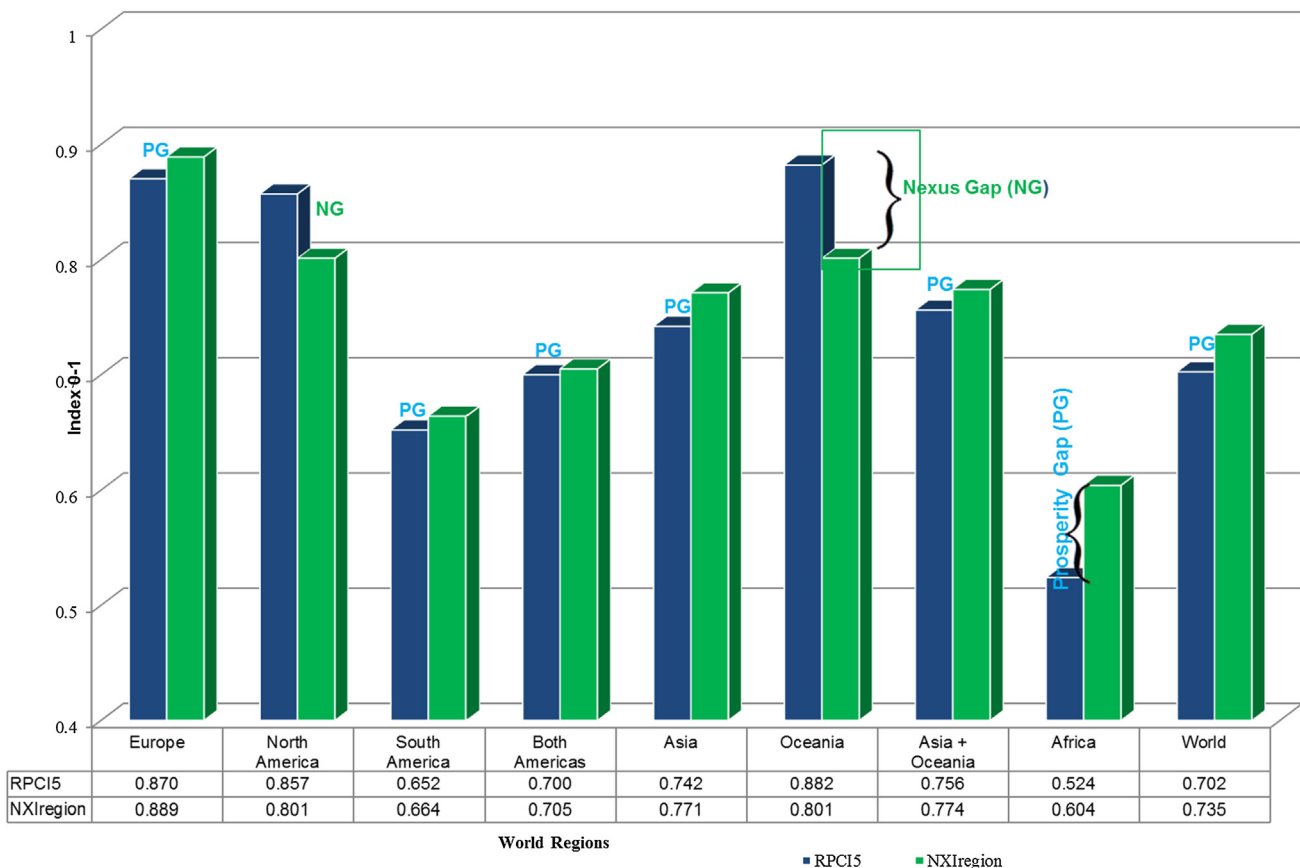
First, we defined the arithmetic mean ($\overline{NXI_{city}}$) as the starting statistical measure:

$$\overline{NXI_{city,r}} = \frac{1}{n} \sum_{i=1}^N (NXI_{i,r}) \quad (10)$$

Based on the arithmetic mean, we calculated the variance of the $NXI_{city,i}$ for the regions.

$$\sigma_r^2 = \frac{1}{n} \sum_{i=1}^N (NXI_{city,i,r} - \overline{NXI_{city,r}})^2 \quad (11)$$

**Nexus gap (NG) prosperity gap (PG) of the cities of the world
NXI_{region} and RCPI⁵**



Source: Own calculations 2017 based on UN-Habitat 2012

IEK-STE 2017

Fig. 7. World city indices.

Table 3

Statistical summary of the Nexus City Index (NXI).

Statistical key numbers of the NXI				
Statistical measure	Europe	Both Americas	Asia + Oceania	Africa
Mean	0.884	0.705	0.779	0.619
Variance	0.003	0.006	0.007	0.012
Standard deviation	0.053	0.078	0.085	0.109
Coefficient of variation	0.060	0.112	0.109	0.176

Source: Own calculation, authors 2016, IEK-STE 2016

We then used the variance of the regional $NXI_{city,i}$ to define the standard deviation:

$$\sigma_r(NXI_{city}) = \sqrt{\sigma_r^2(NXI_{city})} \quad (12)$$

With the standard variation and the arithmetic mean, we defined the coefficient of variation, the statistical measure to summarize the resilience of the regional urban areas.

$$|v_r(NXI_{city})| = \frac{\sigma_r(NXI_{city})}{\overline{NXI_{city,r}}} \quad (13)$$

The coefficient of variation captures the risk of a nonresilient urban situation. Table 3 shows that the European cities have the highest arithmetic mean (0.889) with the lowest variance (0.002), meaning that the European cities are the most resilient and homogeneous group of the analyzed cities. The European cities are followed by the Asian cities (0.785, 0.007), where the variance is slightly higher, i.e. the $NXI_{city,i}$ varies more than in Europe, but the variance is higher than that of the American cities (0.705, 0.006). Thus, Asian cities are, on average, more heterogeneous than the seven American cities. Given the availability of data only for a few selected cities, this may not be representative. Again, we encourage the UN to extend the dataset. As expected, the African cities have the lowest value for the $NXI_{city,i}$ (0.627, 0.011) and the highest variation. This observation is confirmed by the standard deviation. The low standard deviation of the European cities confirms that the city data are close to the mean, whereas the cities in both Americas, Asia and Africa are more heterogeneous and spread farther around the mean. The statistical measure used to capture the dispersion of data points around the mean is the coefficient of variation. The coefficient represents the ratio of the standard deviation to the mean. It is very useful for comparing the degree of variations from one data set to another. The coefficient allows us to determine how much volatility and risk is present in the respective urban system. The lower the coefficient, the better is the risk-return investment trade-off, i.e. the lower the coefficient the better is the pay-off of investment in urban institutions and infrastructure. Regions with a low coefficient of variation such as Europe (0.053) have an institutional infrastructure, which reduces the risk of investment and thereby boosts investments after external shocks and increases the resilience of the city. With increasing coefficients of variation, the risk increases that the cities of the region do not have the ability to respond to ecological and socioeconomic shocks. The institutions have a reduced ability to deal with these shocks, which increases the risk-return relationship of the necessary investment after the shock. In enlarged Asia, the risk increases to 0.103, which is significantly higher than in Europe. Both Americas (0.112) and Africa (0.169) have a significantly higher risk-return relationship than the other two regions. That is to say, the institutions of these regions face severe problems in coping with global challenges.

6. Conclusion and outlook

Our indices enable us to define the nexus and prosperity gap of the cities in the various world regions. They further enable us to

compare individual cities and compare world regions according to their resilience. We thus obtain a top-down and bottom-up picture for the development of the prosperity of cities and of the nexus sectors. Our indices enable decision makers to reduce the complexity of the analyzed system without reducing its underlying complexity, since the indices are based on the comprehensive UN database. The indices can therefore directly serve decision makers to identify and monitor developments in target regions or cities, where the early implementation of measures is necessary in order to prevent or countersteer unsustainable developments which pose a precarious threat to social or ecological stability.

The UN-Habitat reports [40,58] and our indices provide information for planning and managing the urbanization process of the cities of the world with a special focus on development in the FEW nexus sectors. The UN encourages policy makers to develop distributive mechanisms of prosperity, which can contribute to poverty reduction [40]. UN-Habitat assumes that “urban planning and appropriately developed institutions and regulations can play major roles, improving urban equity through the capture and redistribution of rising land values” [40]. Urban planning is central for the FEW nexus sectors [6,62–64].

Our FEW nexus measuring concept enables the assessment of the energy, water and food nexus in urban areas. Furthermore, our approach provides an opportunity to operationalize equity in the nexus analysis, because – as strikingly formulated by the UN – “highly unequal cities are a ticking time bomb waiting to explode” [40]. The approach provides urban institutions with relevant information for the development of political measures to start closing the prosperity and nexus gap. We once again encourage the UN to extend the data basis, especially for South America, in order to obtain a more comprehensive picture of the cities of the world.

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